Proton Spin Structure in the Resonance Region

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We have examined the spin structure of the proton in the region of the nucleon resonances ($1.085\ \text{GeV} < W < 1.910\ \text{GeV}$) at an average four momentum transfer of $Q^2 = 1.3\ \text{GeV}^2$. Using the Jefferson Lab polarized electron beam, a spectrometer, and a polarized solid target, we measured the asymmetries $A_\parallel$ and $A_\perp$ to high precision, and extracted the asymmetries A_1 and A_2, and the spin structure functions g_1 and g_2. We found a notably nonzero $A_\perp$, significant contributions from higher-twist effects, and only weak support for polarized quark-hadron duality.

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Ever since the first polarized EMC experiment found that the proton's spin is not fully carried by its valence quarks [1], the nucleon spin structure has been studied extensively, for example, at SLAC [2], CERN [3], and DESY [4]. The main focus has been on kinematics in the deep inelastic scattering (DIS) region and with large momentum transfer (high Q^2) where observations can be readily interpreted in a perturbative QCD framework. In more recent years, lower energy regimes ($Q^2 \sim 1\ \text{GeV}^2$) have grown in importance, where the transition from the asymptotically free to the bound configuration of the quarks can be probed. Evaluating the requisite moments of the spin structure functions requires data or model dependent extrapolations, up to parton momentum fraction $x = 1$, where the electromagnetic scattering probe interacts with the proton as a whole, including the kinematic region dominated by nucleon resonances.

The new experimental focus on the larger x and lower Q^2 regimes so far has been concentrated on longitudinal polarization as the dominant, and technically more accessible, component. This has limited investigations to the spin structure function g_1, which represents the charge-weighted quark helicity distributions. Because of the success of DIS interpretations based on the naïve parton model, which is limited to longitudinal spin components, little emphasis has been placed on transverse spin studies. In contrast, the operator product expansion (OPE) approach to QCD includes transverse spin starting from leading twist [5,6] and is applicable at all kinematics. Since each higher order of twist, interpretable as increased correlation between partons, adds another $1/Q$ term, higher-twist contributions should be more prominent at low Q^2. Although transverse spin is suppressed in DIS at leading twist, thus motivating the twist-2 WW approximation [7]

$$g_2^{\rm WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 g_1(y, Q^2)\frac{dy}{y}, \quad (1)$$

twist-3 should contribute significantly to g_2. The OPE relates the twist-3 matrix element d_2, which represents quark-gluon correlations, to the third moments of g_1 and g_2 [6],

$$d_2 = 3\int_0^1 x^2(g_2 - g_2^{\rm WW})dx = \int_0^1 x^2(2g_1 + 3g_2)dx, \quad (2)$$

permitting comparison with QCD lattice calculations, and thus providing a clean test of the theory.

Also, the phenomenon of quark-hadron duality [8] has captured much interest [9–13]. This concept connects the perturbative QCD description of quarks and gluons to the hadronic description at lower energies. Whereas global duality relates the entire resonance region to extrapolations of the asymptotic structure functions, local duality relates the extrapolated quantities to restricted resonance regions. Both have been observed in unpolarized scattering [14], but precision measurements of the spin structure functions in the resonance region are needed to determine whether they also display duality. If local duality, as first seen by Bloom and Gilman [8], were observed for g_1, this would not only demonstrate its universal, rather than accidental nature [15], but it could also serve to justify extrapolations. The potential usefulness of the latter for the determination of the moments increases at low Q^2, where the resonances extend over wider ranges of x than at high Q^2.

Experiment E01-006 was conducted in Hall C of the Thomas Jefferson National Accelerator Facility by the Resonance Spin Structure (RSS) Collaboration. Using established procedures and equipment, we have measured the asymmetries $A_\parallel$ and $A_\perp$ in the scattering of polarized electrons off a polarized proton target. These asymmetries are defined as the dimensionless, relative difference between the cross sections with parallel and antiparallel (or perpendicular and antiperpendicular) alignment of the proton and the electron spins. Focusing exclusively on the hadronic vertex, we are left with the virtual photon asymmetries A_1 and A_2, which are functions of the virtual photon's four-momentum-squared $-Q^2$ and the invariant mass W of the final state. Without a measurement of $A_\perp$, this step would require the use of a model or a sweeping assumption. Further, switching from an external scattering view to an internal structure interpretation, we can obtain the spin structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$, where Q^2 is interpretable as the energy scale set by the probe and, in DIS, x represents the fraction of the proton momentum carried by the constituent the probe interacted with. The exact relation between these quantities, and other relevant definitions, can be found in Sec. II of Ref. [2] or in Sec. 2.1 of Ref. [9].

The experiment used Jefferson Lab's continuous, polarized electron beam with energy of 5.755 GeV and a nominal current of 100 nA. The beam polarization was measured by a Møller polarimeter [16] installed upstream of the target, and the beam helicity was flipped at 30 Hz on a pseudorandom basis.

Frozen $^{15}NH_3$, in 1–2 mm fragments, was used as the proton target in the University of Virginia apparatus [17] in which a ^{4}He evaporation refrigerator at 1 K coupled with a 5 T polarizing magnet created a stable polarization environment. The polarization population enhancement was achieved via microwave pumping (dynamic nuclear polarization) and measured by an NMR system using pickup coils embedded in the target material. For the $A_\perp$ measurement, the entire target apparatus was rotated by 90° in the scattering plane. About equal amounts of data were taken with each polarization direction, flipping the nuclear spins by adjusting the microwave frequency, to reduce systematic effects. To maintain uniform polarization in the bulk target material, the beam was continually moved across the face of the target in a 1 cm maximum radius spiral raster pattern around the beam axis. This extra degree of freedom required a dedicated beam position monitor [18] for accurate event reconstruction.

Scattered electrons were detected using the high momentum spectrometer (HMS), positioned at a scattering angle of 13.15°. Two different HMS momentum settings were used, 4.078 and 4.703 GeV, to cover the desired wide range in W, resulting in $0.8 < Q^2 < 1.4$ GeV^2. A detector package consisting of hodoscope planes, wire chambers, a gas Čerenkov counter, and a lead glass calorimeter allowed for particle identification and measurement of the event kinematics. A more detailed description of the apparatus and technique can be found in Ref. [19].

Approximately 160 million scattering events were recorded on the proton target, resulting in highly precise determinations of the parallel and perpendicular asymmetries. These are obtained from observed raw event counting asymmetries which are scaled to 100% polarization and corrected for contamination from radiative and dilution processes:

$$A_{\parallel,\perp} = \frac{1}{fC_N P_b P_t f_{\rm RC}}\frac{N^- - N^+}{N^- + N^+} + A_{\rm RC}. \quad (3)$$

Here, $N^\pm$ is the charge corrected observed yield for the parallel (perpendicular) and antiparallel (antiperpendicular) spin alignment, respectively. P_b and P_t are the beam and target polarizations, f is the dilution factor, C_N is a small ^{15}N nuclear polarization correction, and $f_{\rm RC}$ and $A_{\rm RC}$ are radiative corrections.

The corrected asymmetries $A_\parallel$ and $A_\perp$ are shown in Fig. 1; $A_\perp$ is notably nonzero. The average proton polarization was 62% (70%), and the beam polarization was 71% (66%) during the parallel (perpendicular) running. For the parallel alignment, the product $P_b \times P_t$ was de-

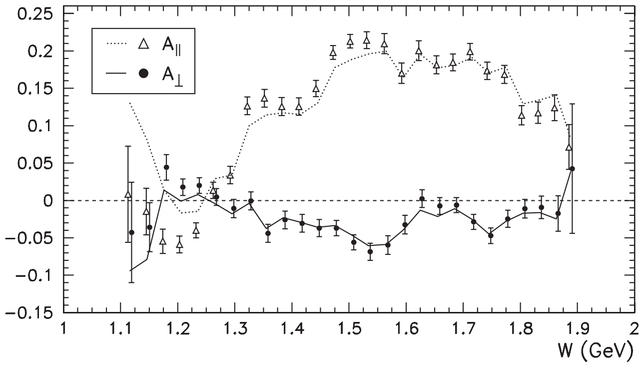

FIG. 1. Our measured asymmetries $A_\parallel$ and $A_\perp$, fully corrected (points) and without radiative corrections (curves).

rived by normalizing the measured elastic asymmetry [19] to the known value, resulting in better accuracy than achievable from direct measurements. In the perpendicular case, the limited knowledge of the elastic asymmetry made the direct measurement of P_b and P_t the better choice. The systematic errors are summarized in Table I, highlighting the lack of models and data for perpendicular radiative corrections.

The dilution factor represents the fraction of events that truly scattered from a polarized proton in the target. It was determined from the ratio of free proton to total target rates calculated via a Monte Carlo simulation which had been matched to calibration data acquired specifically for this purpose. The QFS parametrization [20], modified to improve agreement with our data, was used as input for the Born inelastic cross sections for $A \geq 3$ nuclei. Fits to Hall C inelastic e-p data [21] were used for the H contribution. The unpolarized structure function F_1 and the ratio R of the longitudinal to transverse cross sections are derived from the same fits [21,22]. The uncertainty in these cross sections was the dominant source of systematic error for the dilution correction.

Convoluting radiative prescriptions with models of the resonance region, the elastic peak, and our target, we obtained radiated cross sections and asymmetries. The external radiative corrections were determined using the procedure established in [23], while the POLRAD software [24] was used to determine the internal radiative corrections. The resonance fit model was iteratively improved, until the radiated values matched our experimental data.

TABLE I. Averaged systematic errors in the asymmetries.

Error source	$A_\parallel$	$A_\perp$
Target polarization	1.1%	2.9%
Beam polarization		1.3%
Dilution factor	4.9%	4.9%
Radiative corrections	2.7%	12.9%
Kinematic reconstruction	0.4%	0.4%

The model then trivially provided the corrections to our measurements, with f_{RC} accounting for the radiative dilution from the elastic tail and A_{RC} for all other influences.

We extract the virtual photon asymmetries A_1 and A_2, shown in Fig. 2, from the corrected physics asymmetries $A_\parallel$ and $A_\perp$, using only R as model dependent input. The spin structure functions g_1 and g_2 (Figs. 3 and 4) are then obtained using F_1. The uncertainties in F_1 and R are included in our total systematic error and in the error bands of our plots.

We have fitted the W dependence of our A_1 and A_2 data using an approach similar to that applied to unpolarized cross sections in Ref. [23], substituting for the DIS component a form based on the phenomenological spin structure parametrizations of Refs. [25,26]. These fits served as input in the iterative procedure to obtain our radiative corrections and to calculate the integrals of g_1 and g_2 at constant Q^2. Each spin asymmetry was fitted independently, since they represent different physical quantities.

To test quantitatively for global duality in g_1, we can integrate in x over the resonance region and compare the results obtained from resonance data and DIS extrapolations (Fig. 3). We used our fit to integrate over the resonance region $(1.09 < W < 1.91\ \text{GeV})$ and took the average of the integrals from several DIS extrapolations calculated from target mass corrected [27], next-to-leading order parton distribution functions (NLO PDFs) [28–30] over the same range of W at our average $Q^2 = 1.3\ \text{GeV}^2$. We found the ratio of integrals, PDFs to data, to be 1.17 ± 0.08, indicating agreement at only the two sigma level, and suggesting that PDF extrapolations into the resonance region may not be valid at this Q^2. The ratios for restricted, but still rather broad, W ranges differ from unity by several sigmas, demonstrating that local polarized duality is not valid at our Q^2: $1.09 < W < 1.4$ GeV is 6.47 ± 0.95, and $1.4 < W < 1.91$ GeV is 0.87 ± 0.06. Including also large x resummations for the PDFs [11], the global ratio changed

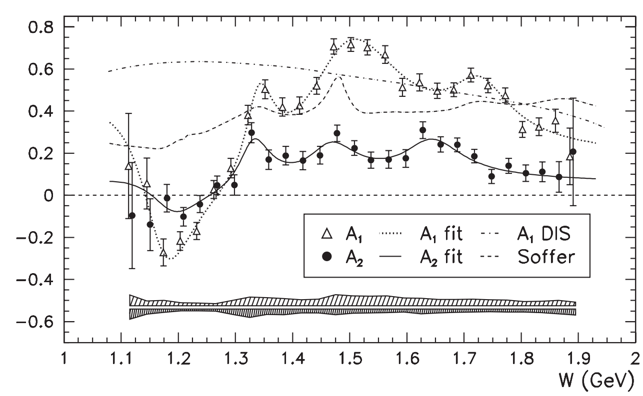

FIG. 2. Virtual photon asymmetries A_1 and A_2 from our data and corresponding fits. Also shown is the E155 fit to DIS data [25,26], evaluated at our (x, Q^2), and the Soffer limit for A_2 [31], based on our A_1 fit. The upper error band indicates the systematic error in A_1, the lower one A_2.

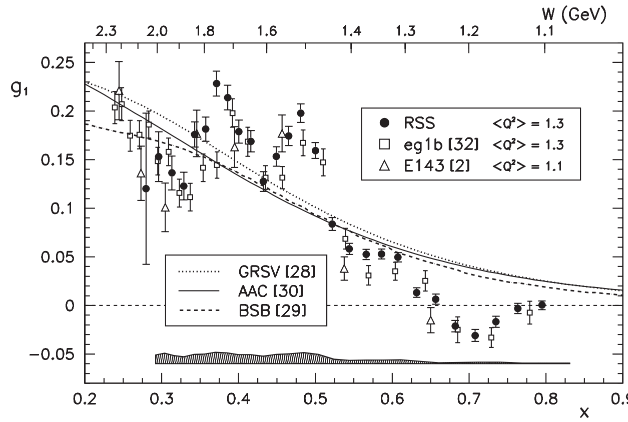

FIG. 3. Results for g_1 from this experiment (RSS) and other relevant data [2,32], as well as target mass corrected NLO PDFs. The upper scale shows W (at $Q^2 = 1.3$ GeV^2) for reference.

to 1.42 ± 0.10. The quoted errors are based on the data integrals only, including a 0.4% contribution from computing our fit at fixed Q^2. Our results are in good agreement with the recent results from CLAS [13].

Approximate global duality within errors was reported by [10], based on A_1 resonance data averaged over a broad Q^2 range from 1.6 to 2.9 GeV^2 and compared to a DIS fit to data. The weak Q^2 dependence of A_1 (within large errors) allows for averaging, instead of calculating the ratio at each Q^2 value as is required for testing duality in the structure functions. But duality in the spin asymmetry $A_1 \propto g_1/F_1$ could be due to accidental cancellations in the ratio g_1/F_1.

Our results for g_2 are much clearer, especially in the framework of the QCD OPE. The comparison of our data and the g_2^{WW} approximation, evaluated from our measurements of g_1, provides strong evidence of the significance of higher-twist terms at this Q^2, as shown in Fig. 4. Combining our measurements of g_1 and g_2, we can investigate specifically the twist-3 contribution via the matrix element d_2 [Eq. (2)]. Over the measured range ($0.29 < x < 0.84$), we find $\bar{d}_2 = 0.0057 \pm 0.0009(\mathrm{stat}) \pm 0.0007(\mathrm{syst})$, including a 4% contribution to the systematic error from our fit's assumed Q^2 dependence. This significantly nonzero result highlights the limitation of leading-twist approximations. Extrapolating this result to $Q^2 = 5$ GeV^2, assuming a $1/Q$ dependence, we find $\bar{d}_2 = 0.0029$ compared to the SLAC result $d_2 = 0.0032 \pm 0.0017$ [33].

In summary, our results significantly increase the available information on the proton spin structure: These new data provide a connection to the measurements at DIS kinematics and fill a significant void in the explored regions. Our measurement with transverse spin arrangement is the first in the resonance region, with notably nonzero results. Our data clearly indicate the importance of higher-twist contributions and thus quark-gluon correlations. We have established that Bloom-Gilman polarized duality is meaningful only for the resonance region as a whole,

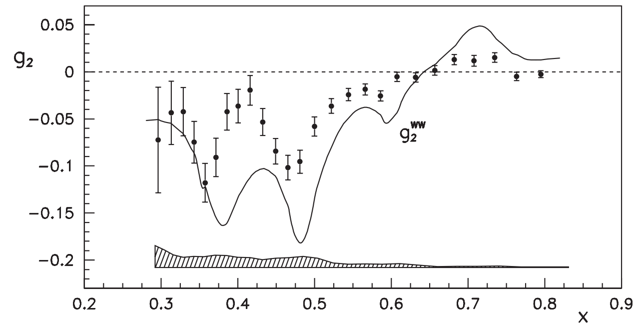

FIG. 4. Our (RSS) values for g_2 and the approximation g_2^{WW} [Eq. (1)] as evaluated from our data.

although local polarized duality may yet be observed at higher Q^2 ranges.

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